

**THE MECHANISM OF ENERGY ABSORPTION VIA
SENSITIVITY ANALYSIS FOR CRASHWORTHY
DESIGN OF COMPOSITE STRUCTURES**

**FINAL PROGRESS REPORT
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13. ABSTRACT (Maximum 200 words) The objectives of the current research are accurate analysis of composite structures under compressive loading and development of efficient analytical sensitivity analysis procedure for application to crashworthy design of composites. A new higher order theory has been developed to study the delamination buckling, postbuckling and growth problem in composite plates and shells. Experimental investigation was performed on delamination buckling and postbuckling of composites with built-in delaminations to evaluate critical load and postbuckling characteristics. The result is a comprehensive data base. Elasticity approach, which accurately models transverse shear and transverse normal deformation, has also been developed. The experimental data base and the elasticity solutions have been used to validate the developed new higher order theory. The research provides a comprehensive investigation on modeling of delaminated composites and an accurate evaluation of limitations of the classical laminate and other improved shear deformation theories. An analytical design sensitivity procedure and a hybrid optimization technique have also been developed for application to improved energy absorption in composites. The procedure is computationally efficient. The hybrid optimization technique allows the simultaneous inclusion of continuous and discrete design variables and is applicable to a wide variety of design problems. The procedure has been used to maximize the energy absorption of composite plates subject to compressive loading and shows significant improvements.				
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A Study of the Mechanism of Energy Absorption via Sensitivity Analysis for Crashworthy Design of Composite Structures

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Objectives

Task 1: Develop accurate modeling techniques for investigating pre- and postbuckling deformation of composites in the presence of delaminations. Validate the theory with experiments.

Task 2: Develop analytical nonlinear sensitivity analysis procedure to analyze the effects of material and geometric changes on the behavior of composite structures, including energy absorption. Apply the procedure to optimize for increased energy absorption.

Task 1 Modeling Delamination in Composites (Graduate Student - Haozhong Gu)

Approach A new higher order laminate theory has been developed to study the delamination buckling, postbuckling and growth problem in composite plates and shells. The refined displacement field proposed in the theory accounts for transverse shear effect through the thickness and is capable of both representing displacement discontinuity conditions at the interface of the delamination as well as satisfying traction-free conditions at the free surfaces and at the delamination interface. An appropriate kinematic description is provided to describe the separation and slipping between the delaminated layer and the substrate. Two and three dimensional elasticity solutions have also been developed for buckling and delamination buckling of composite laminates. The elasticity theory-based buckling equations are derived for each layer of composite. The uniform stress assumption is made for the prebuckling state. It is assumed that delamination separates the laminate across the length and thickness into three regions. The nonlinear eigenvalue problem, used to solve for the critical load, is therefore constructed by using continuity conditions at region and ply interfaces.

Experimental investigation was performed to validate the developed higher order theory for delamination buckling and postbuckling of composites. The compression test of HYE-3574 OH graphite/epoxy composites with built-in delaminations was conducted to evaluate the critical load and the postbuckling load-carrying capacity. The effects of variations in ply stacking sequence, location and length of delamination were studied.

Accomplishments The developed higher order theory is capable of accurately predicting the buckling and postbuckling characteristics of composite plates and shells with pre-existing delaminations. Results computed from the new theory correlate very well with those obtained from developed elasticity solution and existing and generated experimental data. The results show significant deviations from classical laminate theory and first order theory. The deviations are more pronounced for composite shells. It is found that the transverse shear effects are closely related to the delamination location and size and the corresponding buckling modes. In the postbuckling analysis of shells, it is observed that the maximum and minimum loads can be reached in the case of shells with small delamination. In case of large

delamination, a gradual transition from prebuckling membrane behavior to postbuckling is observed. Numerical results computed using elasticity solutions are found to support the above findings made by the new higher order theory. The elasticity solution also reveals that the transverse normal deformation has a less important effect on the critical buckling load of simply-supported plates and the transverse shear effects are much more significant in case of plates with cross ply arrangements than those with angle ply arrangements.

From the experimental study, it is found that composite laminates can retain their load bearing capacity after buckling. The delamination buckling mode is found to be closely related to both the location and the length of delamination. Excellent agreements are observed between the experimental values of the critical load and those predicted by the new higher order theory. Good correlations are also obtained for the initial postbuckling behavior.

Significance The new higher order theory provides an adequate framework for accurate evaluation of transverse shear effects in delaminated composite plates and shells with arbitrary thickness. The procedure is computationally very efficient. Elasticity solutions for buckling and delamination buckling accurately accounts for the transverse shear effect and the transverse normal deformation of composites. They also provide a means for accurate assessment of the limitations of classical laminate theory and other existing improved shear deformation theories. The experimental investigation provides a comprehensive data base, on delamination buckling and postbuckling behavior of composites, for analytical correlations. Such information is not available in the existing literature.

Task 2: Analytical Sensitivity Analysis Procedure (Graduate Student - Ruijiang Guo and Charles E. Seeley)

Approach An elastoplastic deformation theory for responses and sensitivity analyses has been developed. The procedure developed eliminates the need of expensive finite difference-based techniques typically employed to obtain such information as well as reduces the number of experiments required to study such phenomena. A rate-independent constitutive model has been employed to account for the plastic material behavior. A method of design partial differentiation has been developed to solve the rate constitutive equations which results in a set of easy to solve linear differential equations. A direct differentiation technique and a reference domain concept are used for the sensitivity analysis. Based on the theory, a finite element sensitivity analysis procedure has also been developed.

The sensitivity analysis procedure is then used to study the improvements in energy absorption of composite laminates undergoing buckling and postbuckling deformation. An optimization procedure is developed based on a hybrid technique which incorporates continuous and discrete design variables simultaneously. The procedure combines a gradient-based continuous design variable optimization procedure in the traditional simulated annealing algorithm. A multiobjective formulation, known as Kreisselmeier-Steinhauser function approach, is used to combine the objective function and constraints into a single equivalent objective function. A two-point exponential expansion technique is used to approximate the objective function and constraints to reduce the number of costly nonlinear finite element analyses. The procedure developed is used to maximize the energy absorption of composite plates subject to compressive loading.

Accomplishments The finite element based sensitivity analysis procedure has been used to compute the design sensitivities of both isotropic and composite plates undergoing buckling and postbuckling. In composites, both orthotropic and generally anisotropic laminated plates have been analyzed. The results are compared with the finite difference sensitivities. For most part, the results agree very well with those obtained using the finite difference approach. At the critical buckling load, jumps in design sensitivities are observed using both techniques as expected. For higher value of loads, the accuracy of the approximation, used in the analyses, deteriorates thereby increasing the errors in the finite difference sensitivity calculations. Therefore, the results of the present approach are more reliable in this region. The use of the analytical design sensitivities within the hybrid algorithm increases the computational efficiency of the optimization procedure. The procedure yields significant CPU savings (38-49%) over the finite difference approach. Numerical results also show large improvements in the energy absorption capability when compared to a reference design. Changes in the ply stacking sequence, from reference to optimum, support the expected observation that structures that are designed to carry loads in a postbuckled state have a tendency to be highly flexible and experience substantial postbuckling deformation.

Significance The developed sensitivity analysis procedure will serve as an essential tool during optimization of composites for energy absorption. It can also be used to assess the effects of material and geometric property changes on pre- and postbuckling deformations and energy absorption capability of composite structures. The use of a direct differentiation approach based analytical sensitivity analysis within the optimization procedure also yields significant computational savings. It is accurate and computationally efficient.

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Participating Personnel

<u>Name</u>	<u>Degree Earned</u>	<u>Graduation Date</u>	<u>Employment Dates</u>
Haozhong Gu	Ph.D	August, 1996	1/16/93 - 8/15/96
Ruijiang Guo	Ph.D	August, 1996	1/16/93 - 8/15/96

Inventions

Two computer codes have developed for delamination buckling of plates and shells. These are:

- DHOT - P (Delamination Buckling Using Higher Orders Theory - Plates)
- DHOT - S (Delamination Buckling Using Higher Orders Theory - Shells)

A finite element code has also been developed based on the new analytical sensitivity procedure.

- ASAFE (Analysical Sensitivity Analysis Using Finite Elements)

A Hybrid Optimization Procedure has also been developed which can include both continuous and discrete design variables.

- HOT-C (Hybrid Optimization Technique - C)

Technology Transfer

(1) The developed theories on delamination buckling and postbuckling have been of interest to several researchers and the computer code has been requested by various researchers from different countries. The elasticity approaches for buckling of composites with and without delamination have generated significant interest within the composite research community. The procedure developed provides a testbed for bench marking existing shear deformable theories. Several inquiries (industry and academia) have been made regarding the application of the technique.

(2) The research on nonlinear sensitivity analysis and optimization is of significant interest to the crashworthy community. Drs. Richard Boitnott and Karen Jackson, Army Research Laboratory, Hampton, VA, have been very closely involved with the progress. An invited technical paper (by Dr. Jackson) was presented at the AHS Structures Specialists' Meeting held in October 1995, Hampton, VA. Researchers from US. Army Aviation and Troops Command, Fort Eustis, Virginia, have also been technically involved. Sikorsky Aircraft Co. was interested in the research and has donated composite test coupons to the PI for experimental use.

(3) The research has also generated significant interest within Simula Inc., Phoenix, AZ. Simula has provided cost share in the experimental work by providing free access to their composite manufacturing facility as well as by providing free autoclave time and training (to the students).

(4) The hybrid optimization algorithm has generated a lot of interest within the research community. A copy of the computer code has been provided to Boeing Co., Mesa, AZ. Currently, collaborative research is underway with the researchers at Boeing Co. using the hybrid code to investigate optimal tilt rotor design. A copy of the code has also been requested by the researchers at Fort Eustis, VA and the technology transfer is currently underway.